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Authors
Poirier-Pocovi, M
Bailey, BN

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ORIGINAL ARTICLE

Sensitivity analysis of four crop water stress indices to ambient environmental conditions and stomatal conductance

Magalie Poirier-Pocovi[a], Brian N. Bailey[a]*

*For correspondence, E-mail: mdpoirier@ucdavis.edu

[a] University of California, Department of Plant Sciences, One Shields Avenue, Davis, California 95616-8571, U.S.A.

Highlights

- Sensitivity of CWSIs to ambient conditions and stomatal conductance was analyzed.
- Performance was assessed from sensitivity to stomata relative to ambient conditions
- All CWSIs were highly sensitive to wind speed
- All CWSIs performed poorly in shaded conditions
- Two CWSIs performed well in sunny conditions and removed most environmental effects

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ABSTRACT

Crop water stress indices (CWSIs) quantify plant water status based on measurement of plant temperature. The goal of CWSI formulation is to normalize measured leaf temperatures based on reference temperatures to remove sensitivity to ambient environmental conditions (*e.g.*, air temperature, humidity, radiation), while retaining sensitivity to plant water status as reflected by stomatal conductance. This study sought to better understand the sensitivity of these temperatures to ambient environmental conditions, and ultimately how they influence various CWSIs. The surface energy balance was modeled to simulate the impacts of input parameter variation on leaf temperature and reference surface temperatures used to calculate four different CWSIs. The performance of the CWSIs were assessed based on their ability to maximize sensitivity to stomatal conductance while minimizing the relative sensitivity to ambient environmental conditions.

The sensitivity analyses indicated that all four CWSIs performed poorly in shaded conditions, as they had relatively low sensitivity to stomatal conductance and were sensitive to all environmental parameters. Two CWSIs had high sensitivity to stomatal conductance, and low sensitivity to all environmental parameters except wind speed. None of CWSIs could remove sensitivity to all environmental parameters while retaining sensitivity to stomatal conductance.

Keywords: Energy balance equation, crop water stress index, leaf temperature, sensitivity analysis, Morris method, OAT method

1. INTRODUCTION

Water availability is becoming the most limiting factor for crop production in most countries of the world. In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (IPCC, 2014). Adaptive water management techniques (*i.e.*, adjusting the water supply according to the water needs of the crop to decrease water waste) can help adapt to uncertain hydrological conditions due to climate change.

Woody perennial fruit and nut crops generally require extensive and variable irrigation in order to maximize yields or manipulate quality (Patumi *et al.*, 1999; Goldhamer and Beede, 2004; Egea *et al.*, 2009; García-Tejero *et al.*, 2010), and thus there is a need for sensitive, robust, and user-friendly techniques for measurement of tree water status. To provide guidance for irrigation scheduling, crop water stress index (CWSI) approaches have been previously developed to relate leaf and canopy temperatures to plant water stress conditions (Idso, 1982; Jackson *et al.*, 1981; Grant *et al.*, 2007; García-Tejero *et al.*, 2018). The calculation of these indices helps to estimate the water stress of a plant by comparing its leaf or canopy temperature (T_L) with that of a non-water-stressed plant (T_{wet}) and a dry plant (T_{dry}) to formulate a normalized indicator of plant water status (Nanda *et al.*, 2018). Many CWSIs have been proposed that are based on some combination of wet and dry reference surface temperatures, each with the goal of increasing sensitivity of the index to water stress while decreasing sensitivity to environmental conditions (*e.g.*, Jackson *et al.*, 1981; Qiu *et al.*, 1996; Jones *et al.*, 1997, 2002; Jones, 1999; Grant *et al.*, 2007). These CWSIs are typically formulated arbitrarily or loosely based on theoretical arguments, and an objective theoretical evaluation of their performance has yet to be performed. Quantitative evaluation of CWSIs in the natural environment is difficult because controlling or separating the effects of each environmental factor is generally not possible, and measurement errors become compounded with the formulation of the CWSI itself.

In order to better understand how the different CWSIs are influenced by environmental variables, and ultimately the degree to which they are correlated with stomatal conductance, this study proposes to use a mathematical model based on the energy balance equation along with data obtained in an almond orchard to conduct a sensitivity analysis of different CWSIs and the associated temperature values on which they are based. The aims of this study were thus to (1) evaluate the sensitivity of T_{dry}, T_{wet} and T_L to the variation of four important environmental factors (air temperature, relative humidity, absorbed photosynthetically active radiation, and wind speed) and stomatal conductance, (2) evaluate the sensitivity of four CWSIs following to these parameter variations, and (3) determine the best CWSI for inferring plant water status, which we considered¸ as to be the CWSI that has maximal sensitivity to stomatal conductance compared to its sensitivity to environmental conditions.

2. MATERIAL AND METHODS

2.1. Plant material

The range of the parameters in the sensitivity analysis was determined using an experimental dataset collected in a four-year-old almond orchard (*Prunus dulcis* Mill. cv. 'Non Pareil') at the University of California, Davis (altitude: 23 m, on average; 38°32'16"N, 121°47'42"W).

2.2. Sampling strategy

All measurements were collected in the morning between 9:00 am and 12:00 pm in August of 2018. 64 leaves with approximately the same orientation and size were chosen: in the shaded zone inside the canopy (1 leaf × [6 trees × 2 dates + 4 trees × 5 dates]; 10 < PAR < 300 µmol photons m^{-2} s^{-1}), and in the sunny zone outside the canopy (1 leaf × [6 trees × 2 dates + 4 trees × 5 dates]; 700 < PAR < 1750 µmol photons m^{-2} s^{-1}).

2.3. Stomatal conductance measurement

Gas exchange measurements were carried out using a LI-6800 portable photosynthesis system (LI-COR, Inc., Lincoln, NE, USA). One marked leaf was located in the shade and another marked leaf was situated under the sun. A portion of each leaf of interest was placed in a cuvette with a 1 × 3 cm aperture equipped with an LED light source (6800-02B, LI-COR, Inc.). The CO_2 concentration inside the cuvette was set at 400 µmol CO_2 mol^{-1}. The values of stomatal conductance (mol air m^{-2} s^{-1}) were recorded once there was stabilization of the measurement. The air temperature (T_{air}) and relative humidity (*RH*) inside the chamber, was set manually to match ambient conditions as measured by a handheld thermo-hygrometer probe for smartphones (model 800014, TFA® Dostmann GmbH & Co.KG, Wertheim, Germany). Similarly, the light inside the chamber was set to match the flux measured by the external quantum sensor of the LI-6800.

2.4. Description of the surface energy balance model (EBM)

Assuming that heat storage and metabolic heat production are negligible, the energy balance of a leaf is given by the following equation describing a balance between fluxes due to absorbed radiation, convection, and latent cooling (Campbell and Norman, 1998):

$$R_{abs} - \varepsilon_L \sigma T_L^4 - C_p g_H (T_L - T_{air}) - \lambda g_M \frac{e_s(T_L) - e_s(T_{air})RH}{P_{atm}} = 0, \quad (1)$$

where R_{abs} (W m^{-2}) is the absorbed all-wave radiation flux (shortwave (*PAR* and near-infrared radiation) + longwave (emission from sky, ground and leaves)), ε_L is the leaf emissivity which was assumed to be equal to 0.96 (García-Tejero *et al.*, 2018), $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan-Boltzmann constant, T_L (K) is the temperature of the leaf, C_p = 29.3 J mol^{-1} K^{-1} is the specific heat of air, T_{air} (K) is the air temperature outside of the leaf boundary layer, λ = 44 000 J mol^{-1} is the latent heat of vaporization of water at 25 °C, $e_s(T_L)$ and $e_s(T_{air})$ (Pa) are respectively the saturation vapor pressures evaluated at the leaf or air temperature which were calculated using the Tetens equation (Campbell and Norman, 1998), *RH* is the relative humidity of air outside the leaf boundary layer, and P_{atm} (Pa) is the atmospheric pressure which was estimated as a function of elevation following Piedallu and Gégou, (2007). g_H (mol air m^{-2} s^{-1}) is the boundary layer conductance to heat and is calculated by the following equation, which is applicable for wind speed u < 2.5 m s^{-1} (Daudet *et al.*, 1999):

$$\mathrm{g_H} = (10\mathrm{u} + 7.1) \times \frac{12.265}{101300} \times \frac{\mathrm{P_{atm}}}{\mathrm{T_{air}}}. \quad (2)$$

g_M (mol air m^{-2} s^{-1}) is the leaf boundary-layer conductance to moisture and is defined by the following equation:

$$g_M = \frac{0.97\, g_H g_s}{(0.97 g_H) + g_s}, \tag{3}$$

where g_s is the stomatal conductance of the leaf (mol air m^{-2} s^{-1}). R_{abs} was estimated for a leaf fully exposed to the sky as

$$R_{abs} = R_{SW} + R_{LW} \approx \alpha\left(2 \times \frac{PAR}{4.6}\right) + \varepsilon_L \varepsilon_{air} \sigma T_{air}^4, \tag{4}$$

where R_{SW} and R_{LW} (W m^{-2}) are respectively the absorbed shortwave and the longwave radiation fluxes. $\alpha = 0.4$ is the fraction of incident shortwave radiation that is absorbed by the leaf (absorptivity) (Susorova *et al.*, 2013), PAR is the absorbed photosynthetically active photon flux density (μmol m^{-2} s^{-1}; Sager and Mc Farlane, 1997), ε_{air} is the effective emissivity of the air, which was assumed to be $\varepsilon_{air} = 0.5$ (for clear sky; Sicart *et al.*, 2003). The factor of 4.6 converts PAR photon flux to energy flux (Sager and Mc Farlane, 1997), and the factor of 2 approximates the conversion from energy flux in the PAR band to total shortwave energy flux.

For a leaf covered in liquid water, there is no stomatal limitation to transpiration and Eqn. 1 can be written as:

$$R_{abs} - \varepsilon_L \sigma T_{wet}^4 - C_p g_H (T_{wet} - T_{air}) - \lambda 0.97 g_H \frac{e_s(T_{wet}) - e_s(T_{air}) RH}{P_{atm}} = 0, \tag{5}$$

where T_{wet} is the temperature of the wet leaf.

For a non-transpiring leaf, the latent term is zero and Eqn. 1 can be written as:

$$R_{abs} - \varepsilon_L \sigma T_{dry}^4 - C_p g_H (T_{dry} - T_{air}) = 0, \tag{6}$$

where T_{dry} is the temperature of the non-transpiring leaf.

Because of the nonlinear nature of Eqns. 1, 5, and 6, they cannot be solved analytically for temperature. A numerical solution for T_L, T_{wet}, and T_{dry} was obtained using the "Solver" add-in for Microsoft Excel (Office 365 ProPlus for Windows) by varying the temperature value in order to achieve a net energy flux residual as close to zero as possible.

2.5. Crop Water Stress Indices

Several crop water stress indices (CWSIs) were evaluated in this study, which are based on some combination of T_L, T_{wet}, or T_{dry}. A first CWSI based only on T_{dry} and T_L was calculated as follows

$$CWSI_1 = \frac{T_{dry} - T_L}{T_{dry}}. \tag{7}$$

Since $T_{dry} \geq T_L$, $CWSI_1 \geq 0$, with $CWSI_1 = 0$ for a non-transpiring leaf, and $CWSI_1$ increasing as the crop becomes increasingly hydrated.

A second CWSI was calculated as follows (also called $CWSI_{NI/FI}$ by Grant *et al.*, 2007)

$$CWSI_2 = \frac{T_{dry} - T_L}{T_{dry} - T_{wet}}, \tag{8}$$

Since $T_L \geq T_{wet}$, $0 \leq CWSI_2 \leq 1$ in theory. However, unless liquid water is present on the exterior of the leaf under investigation (*e.g.*, rain, dew) or the vapor pressure deficit is zero, T_L will usually be significantly greater than T_{wet}, and thus $CWSI_2$ is unlikely to reach 1 in a fully-irrigated crop.

A third CWSI based only on T_{wet} and T_L was calculated as follows

$$CWSI_3 = \frac{T_L - T_{wet}}{T_{wet}}. \tag{9}$$

Using this approach, $CWSI_3 \geq 0$ in theory, with $CWSI_3$ increasing as the crop dries out.

Finally, a fourth CWSI derived by Jones (1999) is defined as follows

$$I_G = \frac{T_{dry} - T_L}{T_L - T_{wet}}. \tag{10}$$

A strength of this formulation is that it is theoretically proportional to stomatal conductance (Jones *et al.*, 2002), thus making its interpretation in a relative sense straightforward. However, it has the theoretical bounds of $0 \leq I_G \leq \infty$, and thus is not normalized to unity, which is because stomatal conductance is also not bounded.

2.6. Sensitivity analysis

A sensitivity analysis was used to quantify how the changes in environmental factors T_{air}, RH, PAR, and u (inputs) affected T_{dry}, T_{wet}, T_L and the four CWSIs (outputs), and ultimately to infer the expected performance of the CWSIs. For this analysis, a given combination of input parameters were used to determine the associated T_L, T_{wet}, T_{dry} values based on Eqns. 1, 5, and 6, which were then used to calculate each of the four CWSIs (Figure 1).

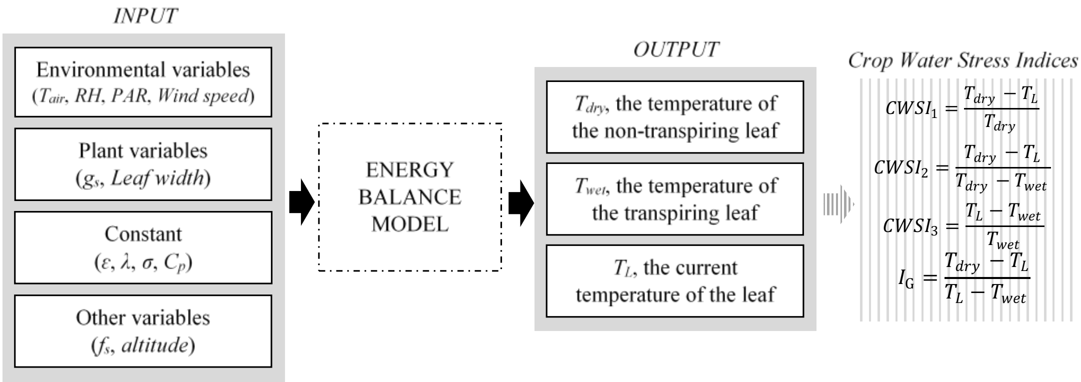

Fig.1: *Schematic representation of the inputs and outputs of the energy balance model and the crop water stress indices.*

The sensitivity analysis in this study utilized two well-known methods. The first was based on the one-factor-at-a-time method (OAT or OFAT method) to individually evaluate the impact of each input parameter on the output. The OAT method involves systematically varying one input variable while keeping others at their baseline (initial) values, and repeating for each of the other inputs in the same way.

A limitation of the OAT method is that it can be heavily dependent on the chosen parameter range and reference values, and that it does not incorporate interactions between input variables. This was addressed by also performing a "global" sensitivity analysis based on the Morris Method (Morris, 1991). The Morris Method randomly samples input parameters to generate a distribution of "elementary effects" of the input parameters on the output. Sensitivity is quantified by calculating the mean of absolute values, μ^*, and standard deviation, σ, of the elementary effects distribution. The relative influence of each input parameter can be ranked based on the magnitude of μ^*, and the relative magnitude of σ with respect to the value of μ^* corresponds to non-linear and/or parameter interaction effects. The calculation of μ^* and σ was performed with the SAFE Toolbox for GNU Octave/MATLAB (Pianosi *et al.* 2015; Eaton *et al*., 2018), with the number of model evaluations chosen to be 2400.

The range of parameter values in the OAT and Morris method sensitivity analyses was based on measurements collected during the experimental campaign in August 2018, and are typical for the California region where almond trees are cultivated (Table 1). In the OAT method, the initial value of the parameters is the central value of the range (Table 1).

Table 1: *Parameter ranges and constant values used in the sensitivity analyses.*

	Parameter / Variable	Definition	Units	Bounds	Initial value
Subject to SA	T_{air}	Air temperature	°C	[15 - 40]	27.5
	RH	Relative humidity	%	[30 - 70]	50
	PAR	Photosynthetically active radiation	μmol photons m^{-2} s^{-1}	Sun: [700 - 1750] Shade: [10 - 300]	Sun: 1225 Shade: 155
	u	Wind speed	m s^{-1}	[0 - 2]	1
	g_s	Stomatal conductance	mol H_2O m^{-2} s^{-1}	Sun: [0.07 – 0.3] Shade: [0.02 – 0.2]	Sun: 0.185 Shade: 0.11
Not subject to SA	l	Width of the leaf	cm	2	
	ε_L	Emissivity of the leaf	dimensionless	0.96	
	ε_{air}	Emissivity of the air	dimensionless	0.5	
	α	Absorptivity	dimensionless	0.4	
	σ	Stefan-Boltzmann constant	W m^{-2} K^{-4}	5.67×10^{-8}	
	λ	Latent heat of vaporization at 25 °C	J mol^{-1}	44000	
	C_p	Specific heat of the air	J mol^{-1} K^{-1}	29.3	
	f_s	Relative humidity of the air immediately above the surface evaporating site	%	100	
	z	Altitude	m	22	

3. RESULTS

The values of T_{dry}, T_{wet}, T_L and the four CWSIs ($CWSI_1$, $CWSI_2$, $CWSI_3$ and I_G) at the initial parameter values (Table 1) are equal to 27.1 °C, 20.6 °C, 24.3 °C, 0.11, 0.44, 0.18 and 0.78 (respectively) in the sun. In the shade, these values decrease and are equal to 20.0 °C, 17.8 °C, 19.3 °C, 0.03, 0.29, 0.09 and 0.41 (respectively).

3.1. Sensitivity analysis of T_{dry}, T_{wet}, T_L and the four CWSIs to the variation of T_{air} based on the OAT method

Figure 2 shows the simulated effect of the individual variation of T_{air} between 15 °C and 40 °C on the models' outputs T_{dry}, T_{wet}, T_L and the four CWSIs in the sun and in the shade. T_{air} had a positive effect on T_{dry}, T_{wet}, T_L, $CWSI_2$ and I_G, and a negative effect on $CWSI_1$ and $CWSI_3$. The sensitivity of T_{dry}, T_{wet}, and T_L to variation in T_{air} were similar.

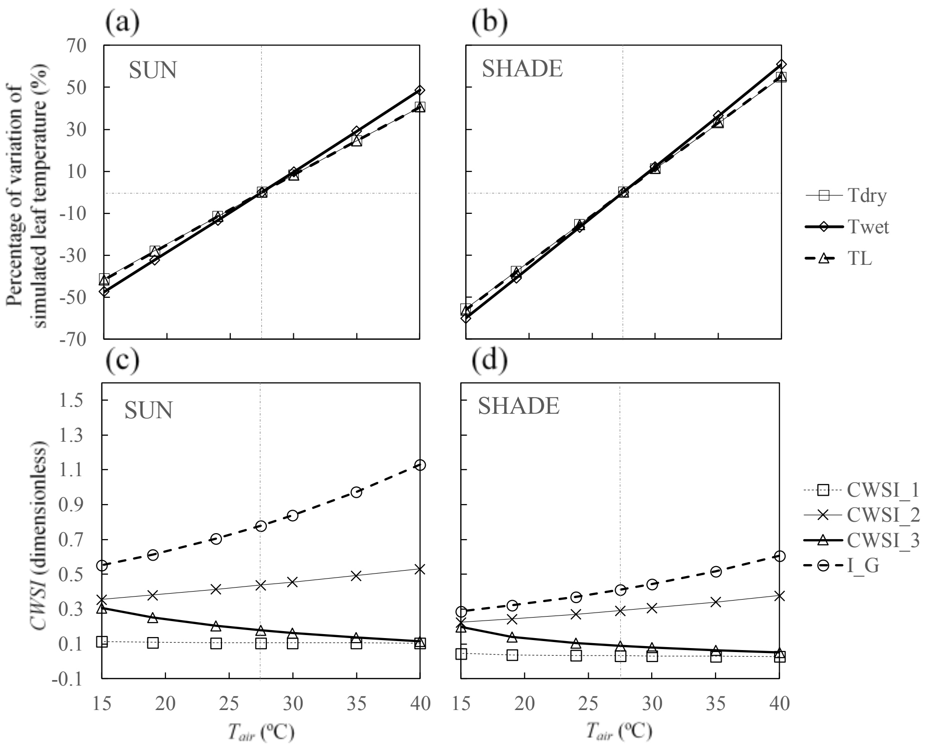

Fig.2: *OAT sensitivity analysis of air temperature. Percentage of variation of the simulated values of T_{dry}, T_{wet}, and T_L (a, b) and four CWSIs (c, d) due to variation in air temperature T_{air} in the sun (a, c) and shade (b, d).*

In the sun (Fig. 2a), the variation of T_{dry}, T_{wet} and T_L was as large as ± 40% over the chosen range of T_{air} (15-40 ^{o}C). In the shade (Fig. 2b), the temperature variation due to T_{air} was up to ± 60%. $CWSI_1$ was the least sensitive and I_G was the most sensitive to the variation of T_{air} in both the sun (Fig. 2c) and in the shade (Fig. 2d). Furthermore, the simulation showed that the sensitivity of $CWSI_1$, $CWSI_2$ and $CWSI_3$ to the variation of T_{air} was essentially the same in the sun and shade. I_G was more sensitive to the variation of T_{air} in the sun than in the shade (Fig. 2c, 2d).

3.2. Sensitivity analysis of T_{dry}, T_{wet}, T_L and the four CWSIs to the variation of RH based on the OAT method

Figure 3 shows the simulated effect of the variation of *RH* between 30 % and 70 % on the models' outputs T_{dry}, T_{wet}, T_L and the four CWSIs in the sun and in the shade.

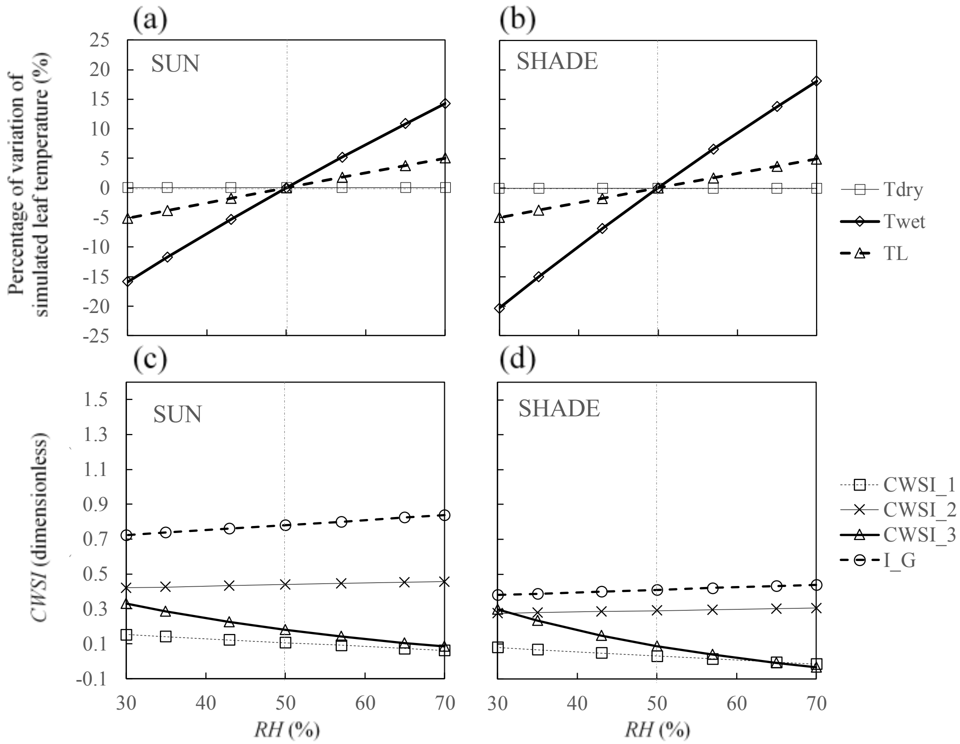

Fig.3: *OAT sensitivity analysis of relative humidity. Percentage of variation of the simulated values of T_{dry}, T_{wet}, and T_L (a, b) and four CWSIs (c, d) due to variation in relative humidity RH in the sun (a, c) and shade (b, d).*

RH had a positive effect on T_{wet}, T_L, $CWSI_2$ and I_G and a negative effect on $CWSI_1$ and $CWSI_3$. T_{dry} is not sensitive to the variation of the relative humidity at constant T_{air} because there is no evaporation (Eqn. 6). The sensitivity of T_L to the variation of RH was up to ± 5% and was the same in the sun and shade (Fig. 3a, 3b). T_{wet} was the most sensitive output to the variation of RH and the effect was higher in the shade than in the sun. In the sun, the variation of T_{wet} to the variation of RH was up to ± 15%. In the shade, it could reach up to about ± 20%. The CWSIs showed the same variations in the sun and in the shade over the range of RH considered.

3.3. Sensitivity analysis of T_{dry}, T_{wet}, T_L and the four CWSIs to the variation of PAR based on the OAT method

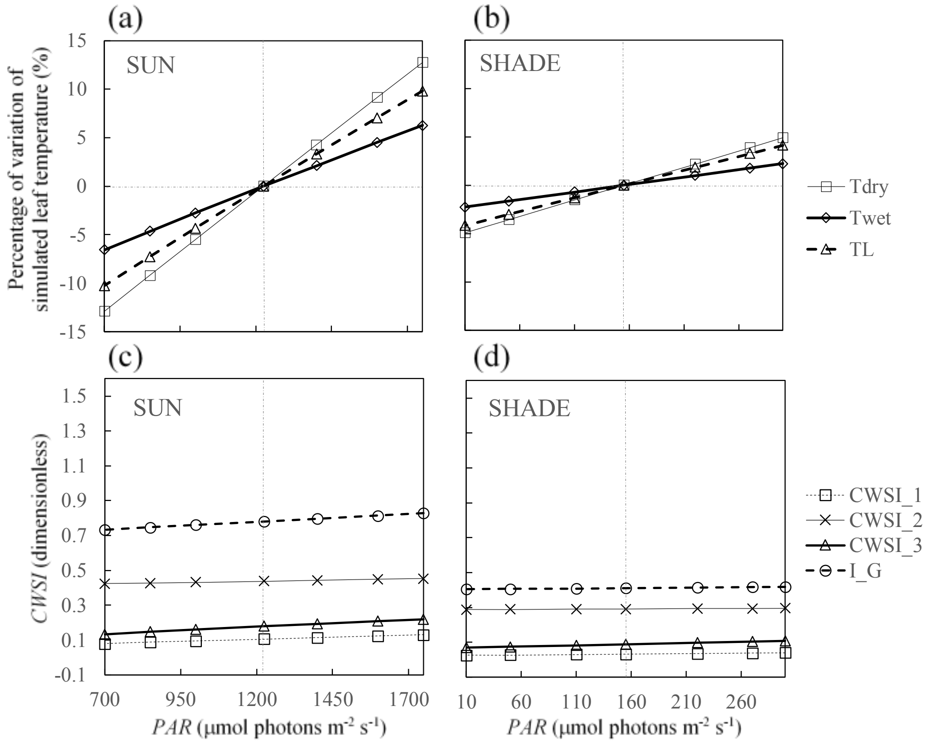

Fig.4: *OAT sensitivity analysis of radiation. Percentage of variation of the simulated values of T_{dry}, T_{wet}, and T_L (a, b) and four CWSIs (c, d) due to variation in photosynthetically active radiation PAR in the sun (a, c) and shade (b, d).*

Figure 4 shows the simulated effect of the variation of *PAR* between 700 and 1750 µmol photons m^{-2} s^{-1} in the sun and between 10 and 300 µmol photons m^{-2} s^{-1} in the shade on the outputs T_{dry}, T_{wet}, T_L and the four CWSIs. *PAR* had a positive effect on all models' outputs. The change in T_{wet}, T_L and T_{dry} over the chosen range of *PAR* were about ± 7 %, ± 10% and ± 13 % in the sun (Fig. 4a). The changes decreased in the shade to about ± 4% for T_{dry} and T_L and about ± 2% for T_{wet} (Fig. 4b). The sensitivities of the four CWSIs to *PAR* were relatively low (variation up to about ± 0.05) in the sun (Fig. 4c) and in the shade (Fig. 4d).

3.4. Sensitivity analysis of T_{dry}, T_{wet}, T_L and the four CWSIs to the variation of u based on the OAT method

Figure 5 shows the simulated effect of the variation of *u* between 0 and 2 m s^{-1} in the sun and in the shade on the models' outputs T_{dry}, T_{wet}, T_L and the four CWSIs.

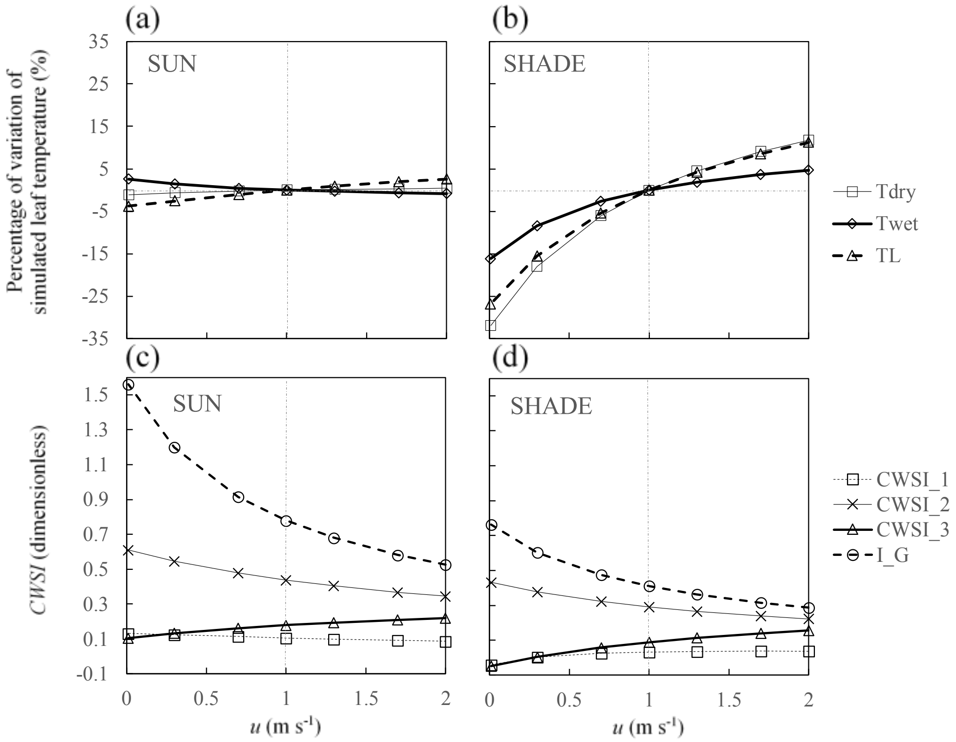

Fig.5: *OAT sensitivity analysis of wind speed. Percentage of variation of the simulated values of T_{dry}, T_{wet}, and T_L (a, b) and four CWSIs (c, d) due to variation in wind speed u in the sun (a, c) and shade (b, d).*

In the sun, u had a positive effect on T_{dry}, T_L and $CWSI_3$ and a negative effect on T_{wet}, $CWSI_1$, $CWSI_2$ and I_G (Fig. 5a, 5c). In the shade, u had a positive effect on T_{dry}, T_{wet}, T_L, $CWSI_3$, $CWSI_1$ and a negative effect on $CWSI_2$ and I_G (Fig. 5b, 5d). In the sun, the leaf temperatures were less influenced by the wind speed than in the shade (variation of the leaf temperatures < ± 5 %; Fig. 5a, 5b). In contrast, in the shade (Fig. 5b), for u > 1 m s^{-1}, the sensitivity of T_{wet} to the variation of u reached up to 5% and about 10 % for T_{dry} and T_L. For u < 1 m s^{-1}, the sensitivity of T_{wet} to the variation of u reached as much as -15% and about -30 % for T_{dry} and T_L. $CWSI_1$ and $CWSI_3$ showed a low sensitivity to the variation of u between 0 and 2 m s^{-1} in the sun and shade. In contrast, I_G had a high sensitivity to the variation of u in the sun, which was higher for the values of u < 1 m s^{-1} (Fig. 5c). In the shade, I_G had a reduced sensitivity to the variation of u compared to sunny conditions (Fig. 5d). $CWSI_2$ had moderate sensitivity to u in both the sun and shade, with sensitivity decreasing in the shade.

3.5. Sensitivity analysis of T_{dry}, T_{wet}, T_L and the four CWSIs to the variation of g_s based on the OAT method

Figure 6 shows the simulated effect of the individual variation of g_s between 0.07 and 0.3 mol m^{-2} s^{-1} in the sun and between 0.02 and 0.2 mol m^{-2} s^{-1} in the shade on the models' outputs T_{dry}, T_{wet}, T_L and the four CWSIs. g_s does not influence T_{dry} and T_{wet} (see Eqn. 1, 5 and 6). The effect on T_L is negative and is more important in the sun than in the shade (Fig. 6a, 6b). For the CWSIs, g_s has a positive effect on $CWSI_1$, $CWSI_2$, I_G and a negative effect on $CWSI_3$. The sensitivities of $CWSI_1$ and $CWSI_3$ to the variation of g_s were very low, relatively low for $CWSI_2$, and high for I_G. The impact of variation of g_s in the shade and in the sun on the CWSIs were the same, except for I_G where the sensitivity to the variation of g_s was higher in the sun than in the shade (Fig. 6c, 6d).

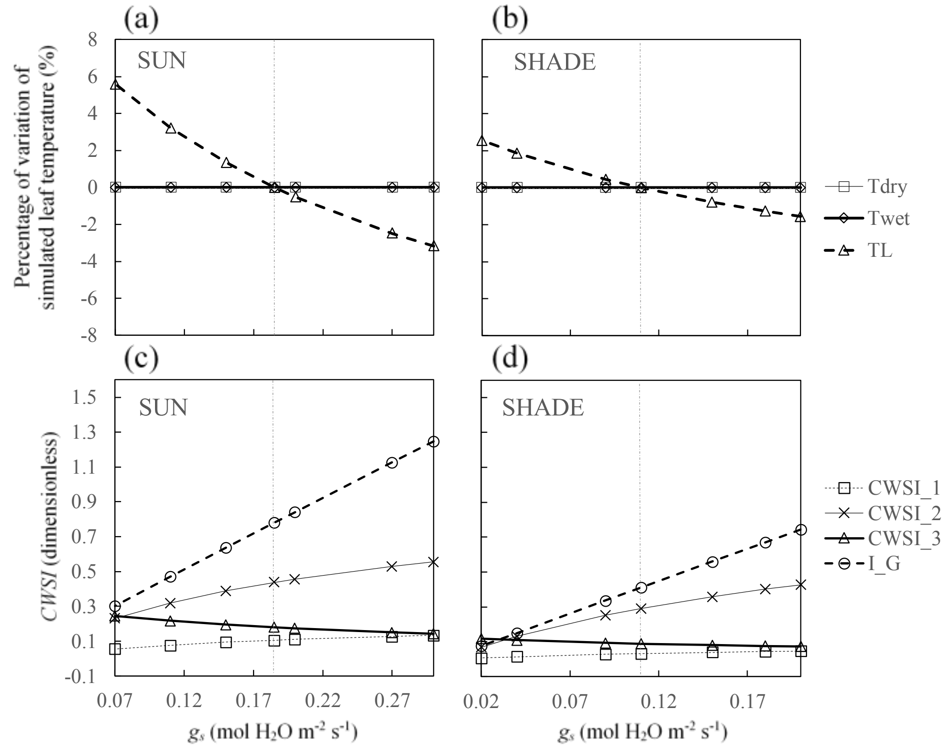

Fig.6: *OAT sensitivity analysis of stomatal conductance. Percentage of variation of the simulated values of T_{dry}, T_{wet}, and T_L (a, b) and four CWSIs (c, d) due to variation in stomatal conductance g_s in the sun (a, c) and shade (b, d).*

3.6. Effect of environmental parameters and stomatal conductance on T_{dry}, T_{wet}, T_L – Results of Morris method

Figure 7 summarizes the results of the sensitivity analysis based on the Morris method for T_{dry}, T_{wet} and T_L in sunny and shaded conditions. Unsurprisingly, T_{dry}, T_{wet} and T_L were principally driven by T_{air} (highest μ*) in the sun (μ* > 17; Fig. 7a, 7c, 7e) and shade (μ* > 21; Fig. 7b, 7d, 7f). The influence of T_{air} on these three variables was approximately linear because the magnitude of σ was at least an order of magnitude less than μ* (Menberg *et al*., 2016). In the sun σ/μ* for T_{air} was 0.05, 0.11 and 0.11, and in the shade σ/μ* was 0.03, 0.07 and 0.04 for T_{dry}, T_{wet} and T_L respectively. This result was in agreement with the curves obtained from the OAT method shown in Fig.

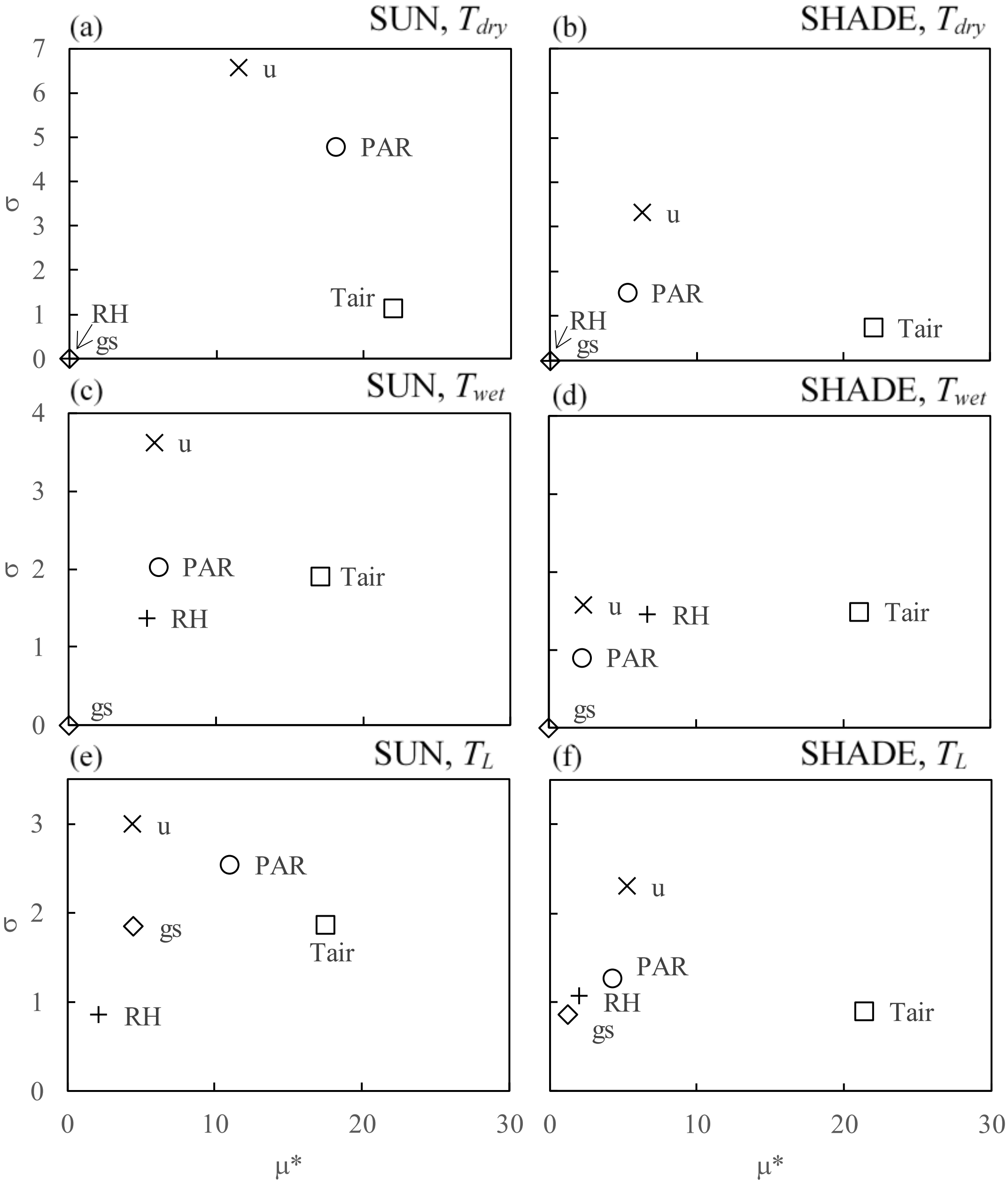

Fig.7: *Global sensitivity analysis of temperature using the Morris method. Mean (μ*) and standard deviation (σ) of the elementary effects of T_{air}, RH, PAR, u, and g_s on T_{dry} (a, b), T_{wet} (c, d) and T_L (e, f) in the sun (a, c, e) and shade (b, d, f).*

2a, 2b, which suggested an approximately linear relationship between surface temperatures and T_{air}. In the shade, the parameters *RH*, g_s, *PAR* and *u* had a lower effect ($\mu^* < 7$) than T_{air} ($\mu^* > 15$). In the sun, T_{dry} and T_L were significantly influenced by *PAR* ($\mu^* \approx 18$ for T_{dry} and $\mu^* \approx 11$ for T_L) and more weakly influenced by the other parameters (*RH*, g_s, *u*). Additionally, T_{wet} was weakly influenced by parameters other than T_{air} in the sun ($\mu^* < 7$; Fig. 7c). Except for T_{air}, the effects of the parameters on the models' outputs in the sun and shade were monotonic or almost monotonic ($0.1 < \sigma/\mu^* < 0.7$; Fig. 7a-f), which was in agreement with the curves obtained from the OAT method shown in Fig. 3-6 (a, b). *u* showed the highest value of σ (Fig. 7), which corresponds to the highly nonlinear curves from the OAT method shown in Fig. 5.

3.7. Effect of environmental parameters and stomatal conductance on CWSIs – Results of Morris method

Figure 8 summarizes the results of the sensitivity analysis based on the Morris method for $CWSI_1$, $CWSI_2$, $CWSI_3$ and I_G in sunny and shaded conditions. Although T_{air} was the most important parameter for T_{dry}, T_{wet}, and T_L, this was not the case for the CWSIs. In the sun, $CWSI_1$ was primarily influenced by *u* and g_s ($\mu^* = 0.114$ and 0.113, respectively) and secondarily by *PAR* ($\mu^* = 0.09$) (Fig. 8a). Their effects on $CWSI_1$ were monotonic ($0.1 < \sigma/\mu^* < 0.5$). Shady conditions decreased the impact of *u*, g_s, *PAR* and T_{air} but increased the effect of *RH* (Fig. 8e). Their effects remained approximately linear and monotonic, except for *u* in which $\sigma/\mu^* > 1$ which suggests that this parameter exhibit either non-linear behavior, interaction effects with other parameters, or both.

$CWSI_2$ was driven mainly by g_s and secondarily by *u* in the sun (highest μ^* of 0.312 and 0.268, respectively; Fig. 8b) and by *u* in the shade ($\mu^* = 36.1$; Fig. 8f). In the sun, the effect of all parameters was monotonic or almost monotonic ($0.1 < \sigma/\mu^* < 0.6$; Fig.

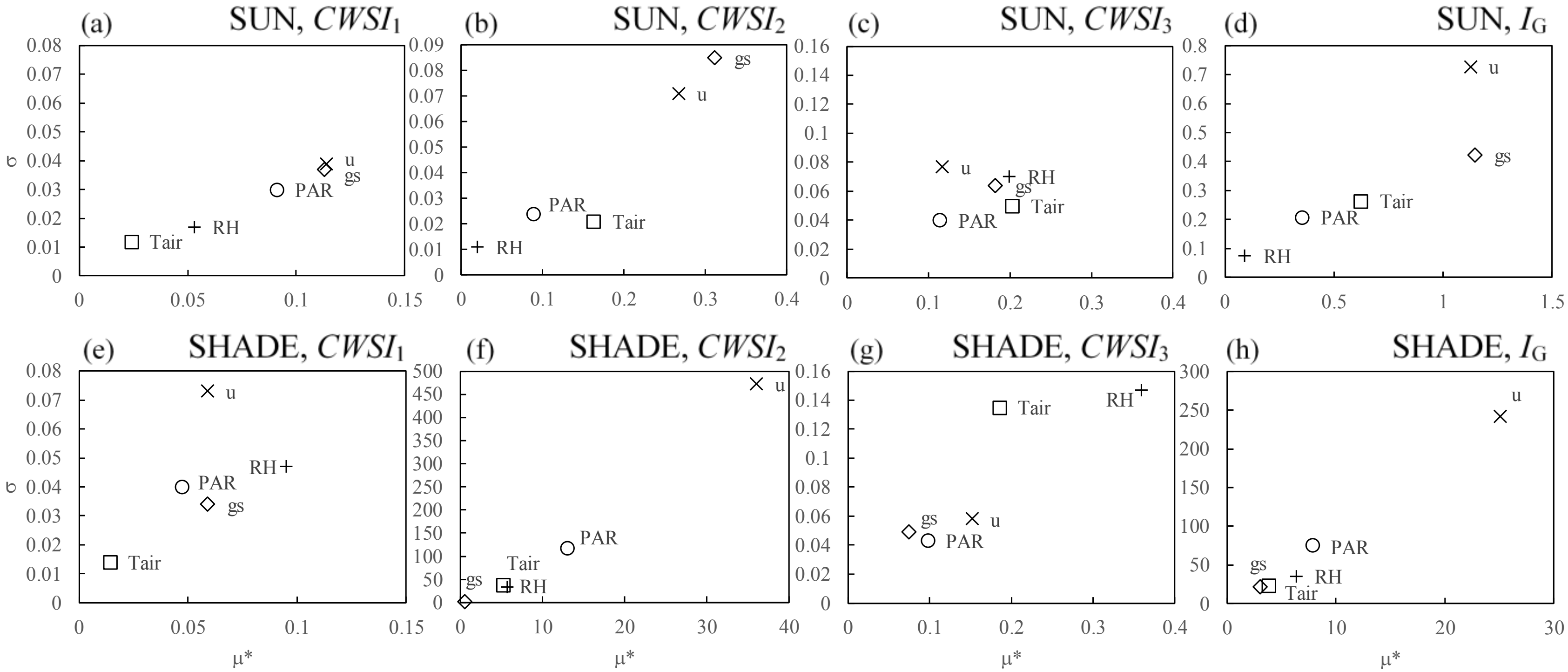

Fig.8: *Global sensitivity analysis of CWSIs using the Morris method. Mean (μ*) and standard deviation (σ) of the elementary effects of* T_{air}*, RH, PAR, u, and* g_s *on* $CWSI_1$ *(a, e),* $CWSI_2$ *(b, f),* $CWSI_3$ *(c, d) and* I_G *(d, h) in the sun (a, b, c, d) and shade (e, f, g, h).*

8b). In the shade, all parameters showed a ratio $\sigma/\mu^* > 1$ which suggested that the parameters exhibited either non-linear behavior, interaction effects with other parameters, or both.

In the sun, all parameters had a similar influence on $CWSI_3$, and their effects were monotonic or almost monotonic ($0.1 < \sigma/\mu^* < 0.7$; Fig. 8c). In the shade, $CWSI_3$ was driven mainly by RH and secondarily by T_{air}. The other parameters had a small effect on $CWSI_3$. RH and T_{air} had monotonic or almost monotonic effects ($0.1 < \sigma/\mu^* < 0.7$; Fig. 8g).

Finally, I_G was driven primarily by g_s in the sun and secondarily by u. The other parameters had a minimal influence on the value of I_G ($\mu^* < 1$). In the shade, I_G was driven primarily by u ($\mu^* = 25.1$). The other parameters had a relatively small impact ($\mu^* < 8$). In the shade, the effects of all parameters were monotonic or almost monotonic ($0.1 < \sigma/\mu^* < 1$). In the sun, they had a ratio $\sigma/\mu^* >> 1$ which suggested that the parameters exhibited either non-linear behavior, interaction effects with other parameters, or both.

4. DISCUSSION

The use of leaf temperature and crop water stress indices to evaluate the water status of plants and manage irrigation requires consideration of ambient environmental factors, and interpretation requires a linkage to the stomatal conductance. Accordingly, we will first discuss the results of the two sensitivity analyses conducted in this study based the effects of environmental conditions and the stomatal conductance on T_{dry}, T_{wet}, T_L and four CWSIs. The sensitivity analysis results were used to compare the different CWSIs and ultimately assess the theoretical performance of the CWSIs.

4.1. Local vs. global sensitivity analysis methods

The advantage of the analysis based on the Morris method is that it provides a global view by examining parameter interactions, which is not taken into account by the OAT method. In general, the OAT method provided insight into the magnitude of the effect of the input parameters (T_{air}, RH, PAR, u, and g_s) on the models' outputs (T_{dry}, T_{wet}, T_L, $CWSI_1$, $CWSI_2$, $CWSI_3$ and I_G), which Morris' method did not provide. Thus, the use of these two methods for sensitivity analysis provided complementary information.

4.2. Effect of environmental parameters and stomatal conductance on T_{dry}, T_{wet} and T_L

The sensitivity analysis showed that increasing PAR (*i.e.*, from shady to sunny conditions) increases the interactions between environmental parameters that influence T_{dry}, T_{wet} and T_L models because their σ increases relative to μ^* (Fig. 7). T_{dry} was more sensitive than T_{wet} and T_L to PAR variation, although PAR still had a significant effect on T_{wet} and T_L (Fig. 4a, 4b, 7a, 7b). The sensitivity of leaf temperature to PAR was highlighted by Agam *et al.* (2013) and Jones *et al.* (2009). Agam *et al.* (2013) observed that variation in CWSI due to abrupt changes in radiation intensity was much larger in water-stressed trees compared to well-watered trees. In their experiments, when the radiation flux decreased from 700 to 200 W m^{-2}, temperatures of well-watered and stressed trees declined by 2 ^{o}C and 4.5 ^{o}C respectively, which is comparable to the reductions found by Jones *et al*. (2009).

Not surprisingly, the sensitivity analysis also showed that T_{air} has a strong effect on leaf temperatures (Woods *et al*., 2018). However, unlike Woods *et al.* 2018, the analysis herein indicated that leaf temperature was most sensitive to air temperature rather than wind speed. It is possible that this is because they considered a range of wind speeds from 0 to 5 m s^{-1} along with a linear model for boundary-layer conductance that does not saturate at large wind speeds. In the shade, T_{dry}, T_{wet} and T_L were all dominated by the air temperature. This would indicate that sunny conditions are likely necessary to capture the effects of water status within temperature measurements because temperatures are not sensitive to g_s in the shade under typical conditions. Intuitively, this makes sense because increasing the radiative term in the energy balance amplifies the latent cooling term and thus the sensitivity of temperature to g_s. Previous work has used the level of variability in leaf temperature within a thermal image as a measure of water stress (Fuchs 1990; Jones *et al.* 2002; González-Dugo *et al*. 2006), which is based on the principle that varying leaf angles creates variability in radiation, and that the sensitivity of leaf temperature to radiation increases with increasing water stress. The results of the present study would tend to support this idea, but also suggests that the discrepancy between the temperature of sunlit and shaded leaves within a thermal image increases with increasing water stress, and thus the level of temperature variability is also likely to capture this effect.

4.3. Effect of environmental parameters and stomatal conductance on the four CWSIs

The ultimate goal in formulating a CWSI is to derive an appropriate normalization of the measured leaf temperature that removes the impacts of ambient environmental conditions (namely PAR, RH, T_{air}, and u) and leaves only a dependence on g_s and thus water stress. While many CWSIs have been previously proposed, their effectiveness at performing this normalization has typically not been directly investigated theoretically. Jones (1999) examined the impact of u on several CWSIs including I_G and found that u had a significant influence on all CWSIs considered, which was also the case for all CWSIs investigated in this work (Fig. 8). Similarly, O'Toole and Hatfield (1983) found $CWSI_2$ to be very sensitive to u, which made estimating the CWSI from meteorological measurements problematic in some cases. For both $CWSI_2$ and I_G, the most important parameters (in the sun) were u and g_s with all other parameters playing a lesser role. Since the boundary-layer conductance g_H depends only on u, ang g_s and g_H together control the water flux, it makes sense that these CWSIs should be most sensitive to u and g_s. In contrast, under sunny conditions $CWSI_1$ was most sensitive to u, g_s, and PAR, and $CWSI_3$ was sensitive to all parameters. This result indicates that the normalizations used in $CWSI_1$ and $CWSI_3$, which use only one of either T_{wet} or T_{dry}, were ineffective at removing sensitivity of the CWSI to environmental conditions. Intuitively, one would expect that effective normalization would require both T_{wet} and T_{dry} in order to account for both the effects of radiation and convection (T_{dry}) as well as evaporation (T_{wet}) on the leaf temperature T_L. However, recent work by (Poirier-Pocovi *et al., submitted*) found that both T_{wet} and T_{dry} could be easily and accurately estimated from the temperature of a dry piece of green paper under a wide range of environmental conditions, which suggests that a proper normalization may not necessarily require an evaporating reference surface. The Morris sensitivity analysis (Fig. 7) may support this idea, as it indicated that T_{wet} was determined mainly by T_{air}, and only to a lesser extent by RH. If this is indeed the case that T_L is not particularly sensitive to RH, one could reasonably expect that $CWSI_1$, which normalizes using only T_{dry}, would perform well. While $CWSI_1$ does a fairly good job at removing the effect of RH, it increased sensitivity to PAR in comparison with $CWSI_3$ and I_G. This could be because T_{dry} is also very sensitive to PAR (Fig. 7), and thus basing the CWSI normalization (particularly the denominator) on only T_{dry} appears to increase its sensitivity to PAR.

In shady conditions, all CWSIs performed poorly, with relatively low sensitivity to g_s and high sensitivity to all environmental parameters. Agam *et al.* (2013) also observed that $CWSI_2$ had a much weaker correlation with g_s under shady versus sunny conditions. In the absence of strong radiation forcing, the leaf temperature is primarily determined by the air temperature (Fig. 7) and thus evaporative cooling plays a lesser role. As such, leaf temperature is generally not likely to be a good indicator of plant water status as inferred through g_s.

Interestingly, in shady conditions I_G was highly sensitive to u, with all other parameters playing a lesser role. Because of this, it is possible that some variation of I_G in the shade could be used to develop a normalization that removes the strong and undesirable effect of u in $CWSI_2$ and I_G. However, this requires experimental testing since, although I_G is deemed "sensitive" to u in the shade in a relative sense based on the Morris sensitivity parameters, all energy fluxes are relatively small in the shade and thus it is unclear whether the signal from u would be robust. However, the results of the OAT analysis suggest that T_L has high absolute sensitivity to u in the shade, in fact more so than in the sun (Fig. 5).

5. CONCLUSION AND RECOMMENDATION

Our results suggest several recommendations for infrared measurement of leaf temperature and the use of CWSIs to estimate plant water status. We considered the best CWSI to be one that has maximal sensitivity to g_s and minimal sensitivity to environmental conditions, which in terms of the Morris sensitivity analysis, would be the CWSI in which the μ* value of g_s was largest relative to the μ* of environmental variables. Additionally, if a variable's σ value is comparable in magnitude to its μ* value, caution is required in interpreting its sensitivity as it could indicate the presence of non-linearities or interactions that could make results dependent on the choice of parameter ranges.

$CWSI_2$ and I_G showed similar performance in terms of the sensitivity analysis. Both were most sensitive to g_s and u, with other environmental variables playing a lesser role. One could argue that I_G is preferable based on the desirable trait that it is proportional to g_s and thus making interpretation with respect to plant water status more straight-forward. However, $CWSI_2$ was slightly more sensitive to g_s in comparison with other variables than I_G including u. Additionally, the ratio of σ/μ* for u in I_G is relatively large indicating the possibility of a non-linear impact, whereas $CWSI_2$ has the desirable trait that all environmental variables appear to have a linear impact. Future work could further improve calculation of CWSIs by focusing on developing a normalization that can remove the impact of u.

According to the results of the sensitivity analysis, it is not recommended measure CWSIs in shaded conditions, but rather to perform measurements in full sun (*i.e.*, PAR>700 μmol m^{-2} s^{-1}). The lack of strong radiative forcing increases the impact of other environmental variables such as T_{air} and decreases the impact of g_s.

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